Summary of the Final Report

14 November 2012

Presented by:
Dr. James Garvin
on behalf of
Chairman *O. Figueroa*

MPPG

Mars Program Planning Group

Introduction and Context

- The MPPG effort was initiated by NASA in March 2012, motivated by:
  - The need to re-plan a U.S. Mars program in light of the President's FY2013 Budget Submittal
  - The NRC 2011 Planetary Science Decadal Survey recommendations for Mars exploration in the context of the budget submittal, and subsequent new discoveries
  - The POTUS challenge for humans in Mars orbit in the 2030s

- The purpose of the MPPG was to develop foundations for a program-level architecture for robotic exploration of Mars that is consistent with the President's challenge of sending humans to Mars in the decade of the 2030s, yet remain responsive to the primary scientific goals of the 2011 NRC Decadal Survey for Planetary Science.

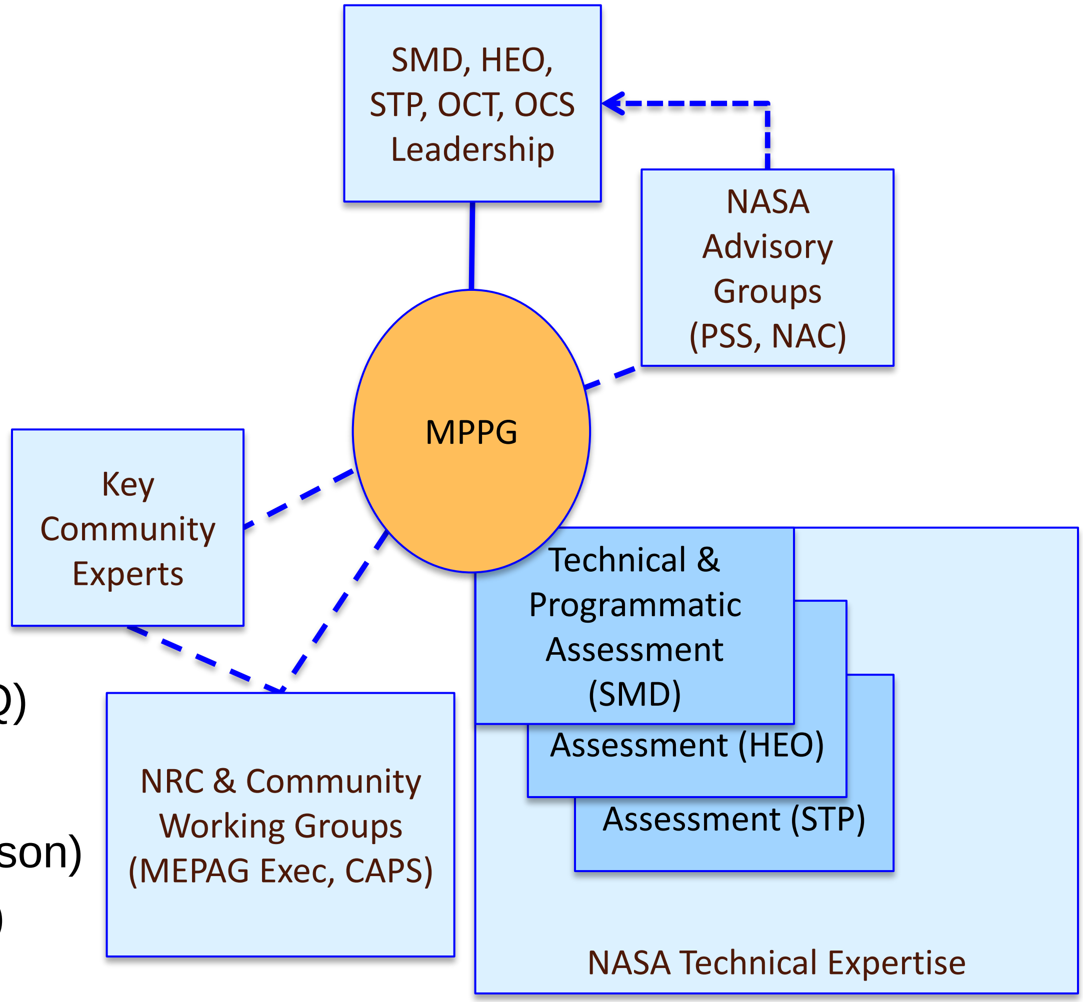
- Consistent with its charter, MPPG reached out to internal and external science, technology and engineering communities, to develop mission options and program architecture alternatives for NASA's consideration

MPPG Core Team & Approach

- Orlando Figueroa (Chair)
- Jim Garvin (SMD/GSFC)
- Michele Gates (HEOMD/HQ)
- Randy Lillard (STP/HQ)
- Dan McCleese (JPL)
- Jack Mustard (Brown Univ.)
- Firouz Naderi (JPL)
- Lisa Pratt (Indiana Univ.)
- John Shannon (HEOMD/HQ)
- George Tahu (Exec Officer, HQ)

Ex-Officio

- Ramon DePaula (SMD/Intl Liaison)
- Mike Wargo (HEOMD/Science)



Objectives and Constraints

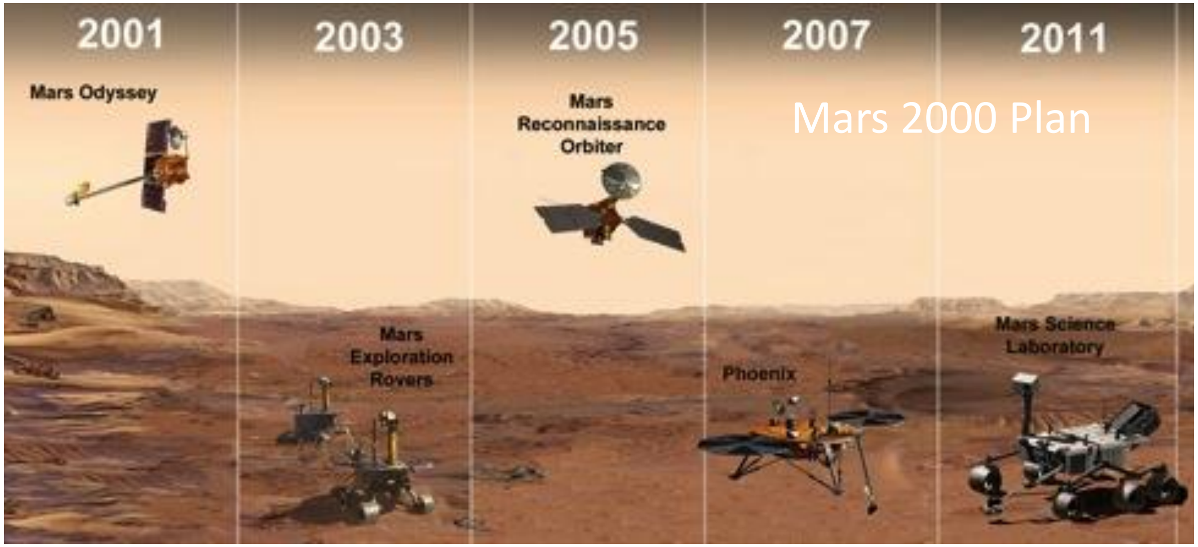
- MPPG was chartered to provide options that integrate science, human exploration and technology at an Agency level with Mars Exploration as a common objective

- **Critical Boundary Conditions**
  - NASA FY13 Budget submittal through FY2017
  - Imperative for strategic collaboration between HEOMD, Science, Technology
  - Remain responsive to the primary scientific goals of the NRC Decadal Survey

- The immediate focus of the MPPG was on the collection of multiple mission concept options for the 2018/2020 Mars launch opportunities.

- To maintain the successful strategic structure of the MEP, and ensure relevancy of the possible 2018/2020 missions to the longer term science and exploration priorities, MPPG was asked to provide notional architecture/pathways spanning to the 2030s

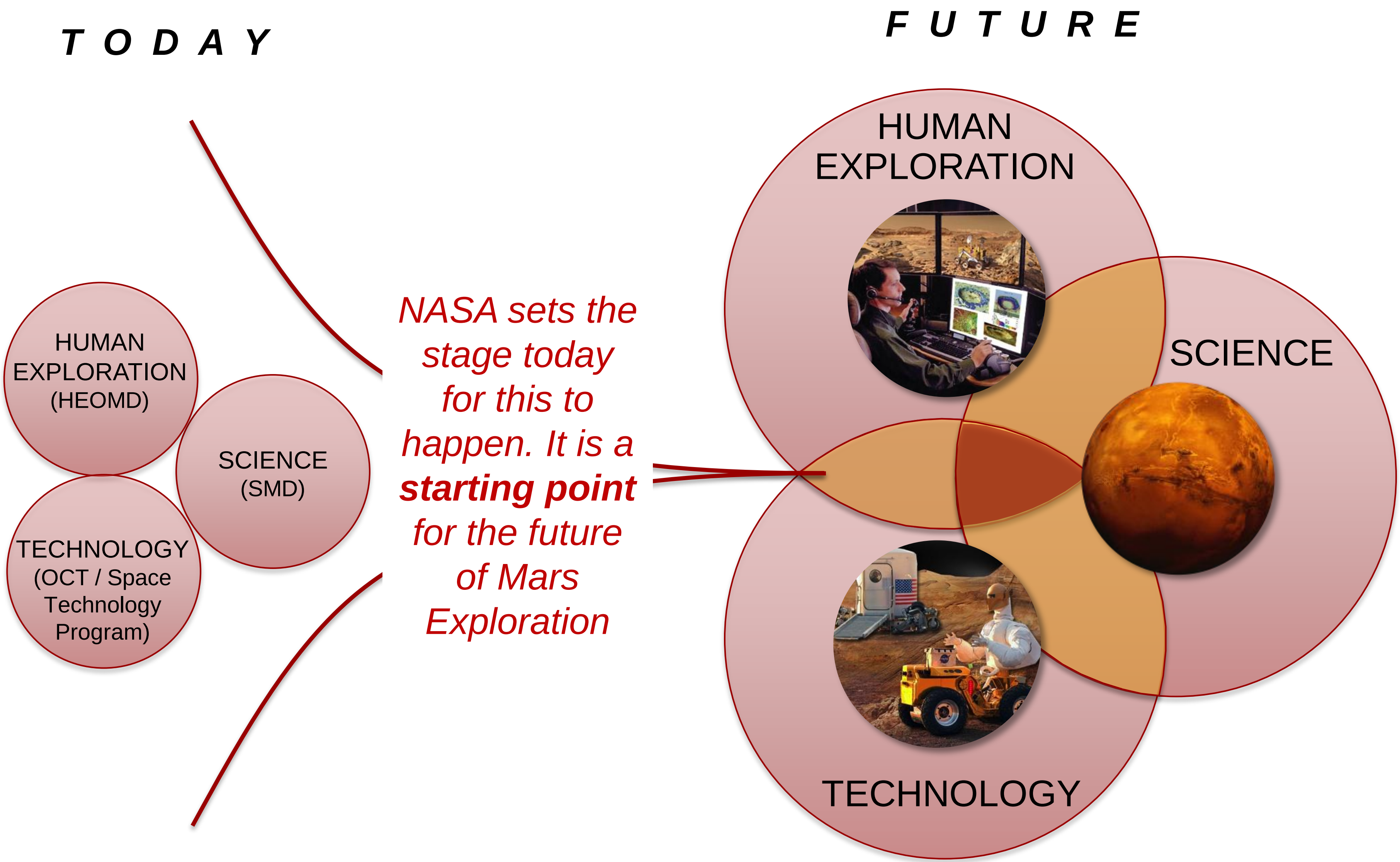
The Mars 2000 Plan and MPPG



- MPPG approach to planning retained the key features of the highly successful and resilient Mars 2000 Plan.
  - A science theme and overarching program strategy, reflected in the sequence of interconnected strategic missions, with competed opportunities "Scouts" (Phoenix and MAVEN) for other Mars science; InSight (a Discovery mission for 2016) will contribute to the science legacy

- An extraordinary decade of scientific discovery, created by the Mars Exploration strategy which was scripted in the summer of 2000, ends with the promise of the Mars Science Laboratory

Mars Exploration as a Common Goal for NASA



MPPG - The Bottom Line

- MPPG explored many options and alternatives for creating a meaningful collaboration between science and human exploration of Mars, while leveraging and focusing technology investments towards a common goal.

- The MPPG finds that sample return architectures provide a promising intersection of objectives and integrated strategy for long term SMD/HEOMD/STP collaboration

- Multiple program architectures can be assembled by varying the scope, sequence, and risk posture assumed for the building blocks provided and analyzed by MPPG; NASA can choose from these to build a program strategy consistent with its long term objectives

Topics Covered

1. Science Pathways
2. Workshop at LPI
    a. Results in the context of MPPG
3. Collaboration between Human Exploration and Science
4. Cross-cutting and Enabling Technologies
5. Possible Program Architectures – Pathway Implementations
    a. Science Pathways A1, A2 and B
    b. Orbital and Landed Platforms
    c. Cost Picture and the Early Opportunities
6. Other Programmatic Considerations
    a. International Collaboration
    b. R&A, Instrument Technology Investments, E&PO
7. MPPG Summary

SCIENCE PATHWAYS

What are Scientific PATHWAYS?

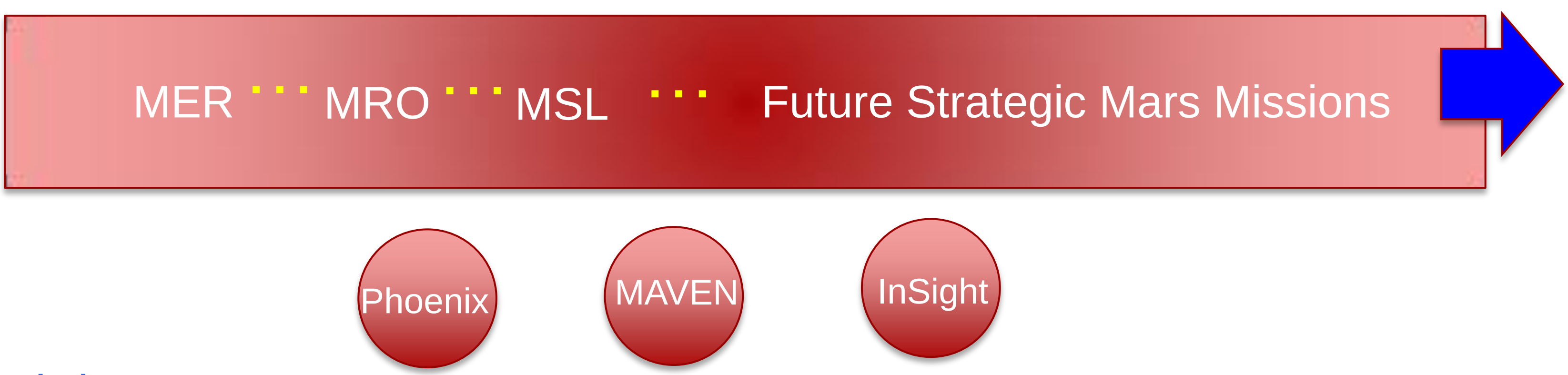
- The Mars exploration strategy of the last decade proved to be extraordinarily productive scientifically
  - 2000 re-planning provided a critical trajectory for science and implementation

- **Discovery-driven Scientific [redacted]:**
  - First employed in the 2000 Mars [redacted]planning effort, pathways include *strategic* plans for science and m[redacted]ram analysis, and active community participation
  - MPPG employed pathways as a [redacted]alyze options as:
    - Foundation for a more *strate*[redacted]tion between SMD/HEOMD/OCT/OCS to[redacted]mon Agency-level goal
    - Catalysts for new scientific [redacted]deas, and advances in technology
  - Pathways helped establish early [redacted]mmon understanding, and intersections

Strategic versus Stand-alone Missions

- Mars exploration in SMD has had (*and should have*) two types of missions:
  - **Strategic missions**: A mission within a chain of strategically laid-out, coupled missions that follow a common scientific line of inquiry
  - **Stand-alone missions**: A single isolated mission accomplishing a significant science objective, but independent from the primary scientific strategy
    - These missions were formerly part of the Mars Exploration Program and competed as *Scouts* (Phoenix and MAVEN)
    - Now no longer within the Mars Program, they compete with other planetary science as a part of *Discovery Program* (InSight)

Sequence of Strategic Missions



Stand-alone Missions:
Previously within Mars Program (Scouts)
Now compete with other science in Discovery Program

MPPG Science Traceability – Candidate Pathways

Science Questions	Science Pathways	Functional Requirements (Examples)	Architecture	NRC/MEPAG Priorities
NRC Decadal Survey, MEPAG Goals (includes HEO needs via SKG's)	Search for Signs of Past Life	Context & *in situ* analysis, sample preservation, sample return	Commence sample return using existing data	Highest priority science and approach
			In situ exploration prior to returning optimal suite of samples	Highest priority science
		In situ analysis for bio-signatures and organics	Measurements can be included in sample return architectures, or via stand-alone surface astrobiology observatory	High priority science, lower priority approach, higher science risk
	Modern Environments as Habitats	*In situ* and orbital measurements. Vehicles depend on findings (orbiter, rover, deep drill)	Depends on new discoveries, and challenges (e.g., planetary protection)	Consistent with NRC Decadal recommendation for competition as *Discovery* or future *New Frontiers* missions
	Dynamics/ Interior	Surface Networks; Active Geophysical Experiments	Multiple static landers with long term monitoring	
	Mars Systems Science	Orbital & Surface measurements	Missions respond to discoveries	

Seek Signs of Past Life – Highest Priority Science

Pathways A1 and A2

Commence Sample Return using existing data

- Search for signs of past life with samples collected from a site--identified using existing data--and returned to Earth for analysis
- This is most directly responsive to the NRC Decadal Survey recommendations
- Collect scientifically-selected samples from a site which has been determined to have astrobiological significance
- Timing of returned samples paced solely by available funds, not further scientific discoveries

Pathway B

Multi-site Investigation to Optimize Search for Past Life

- Search for signs of past life through in situ observations and ultimately analysis of carefully selected samples returned to Earth
- Sample Return commences only after in situ measurements and sampling of multiple sites (3) and Science Community decision process as to which to return to Earth
- The emphasis of this pathway is searching for samples capable of preserving evidence of past life

Pathway A: Commence Sample Return

Objective: Search for signs of past life with samples collected from a site - determined to have astrobiological significance using existing data--and returned to Earth for analysis

- Highest priority large mission recommended by the NRC Decadal Survey
- Relative to NRC Decadal suggested plan, MPPG mission concepts have reduced cost
- Site for MSR is chosen on the basis of current and continuing Mars orbiter remote sensing observations

- **Pathway A** further breaks down into the following two candidate implementation options:
  - Pathway A1: Objectives of MSR distributed across multiple focused spacecraft, multiple launches (3-4 missions)
  - Pathway A2: Combine functions into a smaller set (1-2) of larger multifunction spacecraft, and opportunity for lower total cost

Pathway B: Investigate Multiple Sites Before Commencing Sample Return

Objective: Search for signs of past life through in-situ observations and selection of samples at multiple sites (3). Using in-situ information, Science Community selects optimal sample suite to be returned to Earth.

Pathway B reflects challenges experienced when searching for signs of past life on Earth:

- Preservation of biological signatures is rare on Earth, and investigations at multiple sites on Mars dramatically improves the probability of identifying biologically-relevant samples
  - Sites visited chosen on the basis of orbiter remote sensing observations
  - Samples would be returned from site where in-situ measurements show that rock units formed under conditions most favorable for habitability and bio-signature preservation

"Modern Environments as Habitats" as a Pathway?

MPPG

Objective: Investigate alternative pathways not aligned with NRC Decadal Survey recommendations, including "modern environments as habitats" (Extant Life Systems)

- New discoveries since the NRC Decadal Survey may suggest liquid water on or near the surface (*if confirmed, program could seek extant life systems*)
- Community experts strongly advocated that this line of scientific inquiry (applies to others) not aligned with "Seeking Signs of Past Life" theme (i.e., Pathways A and B), be openly competed as payloads on MEP strategic missions, or as stand alone missions in *Discovery*, and judged on the basis of its intrinsic scientific merit as compared to others
- <u>Specific to "Modern Environments as Habitats":</u>
  - Measurements are only preliminary and immature, and pursuit and understanding of modern habitats or extant life poses scientific risks (with post Viking consequences)
  - Premature given progress and evidence that continue to validate the pursuit of the ancient life theme for the past ~16 years
  - If signs of past life are discovered there would be a greater imperative to search for extant life systems
  - Orbital reconnaissance and pursuit of understanding of new settings (putative brine flows, permafrost, exposed surface ice, trace gas vents) is underway and requires more time to be complete (MRO, MAVEN, ESA/RSA TGO)

Mars System Science as a Pathway?

Objective: Faced with the complex history and physical diversity of Mars, advance Mars System Science in order to fill critical knowledge gaps prior to an undertaking as challenging as human exploration while responding to new discoveries about "active environments on Mars" (relevant to future Sample Return science possibilities or others)

- This pathway seeks to improve our fundamental understanding of Mars' surface and interior in order to better inform the search for evidence of life before undertaking Sample Return and/or human exploration (surface)
- This pathway could be the path of choice if MSL revealed significant misinterpretations of orbital observations of the Gale Crater region and history
- There are multiple alternative foci within this pathway, including attention to the thermal evolution of the Martian crust and deeper interior and volcanism
- On the basis of discussions with Community Experts and analysis by MPPG members, this pathway was REJECTED because:
    - *Elements of this pathway are well-suited for open competition within AO-based opportunities such as SALMON payload selection (MoO's), Discovery or New Frontiers*

WORKSHOP AT THE LUNAR & PLANETARY INSTITUTE

Mars Concepts & Approaches Workshop

Hosted by Lunar & Planetary Institute (LPI), June 12-14, 2012

- Workshop forum organized by Lunar and Planetary Institute (LPI) for the community to discuss ideas and approaches for Mars exploration
- Included both near-term (2018-2024) and longer-term (2024-2030's) timeframes
- Included both science approaches (missions, payloads, strategies) and engineering & technology approaches (mobility, sample collection and return, aerial platforms)
- LPI summary report submitted to NASA: June 18, 2012

Participation Statistics	
Abstracts Submitted:	390
Abstracts Selected for Presentation:	170
Abstracts Selected for Print Only:	146
Participating Countries	10

LPI Workshop – The Results in Context of MPPG

Workshop summarized near-term science, mission and technology concepts for robotic Mars missions that support the Mars community consensus science goals, especially as delineated in the 2013-2022 Planetary Science Decadal Survey.

(see Mackwell et al., 2012, http://www.lpi.usra.edu/meetings/marsconcepts2012/)

[redacted]ample Return (MSR)

[redacted]ayloads, strategies)

[redacted]ts to understand planetary

[redacted]udies

[redacted] processes/escape

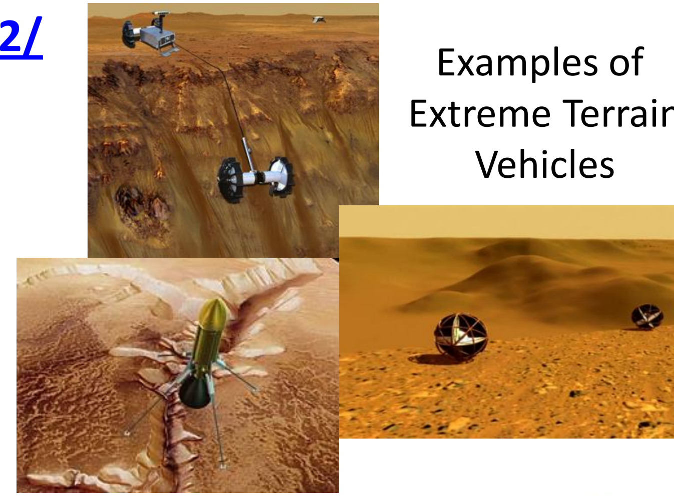
[redacted]omposition

[redacted]

LPI Workshop – The Results in Context of MPPG

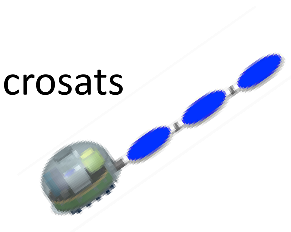
http://www.lpi.usra.edu/meetings/marsconcepts2012/

Expanded the trade space for alternative concepts to access the surface, sampling/analysis instrumentation, and surface system capabilities

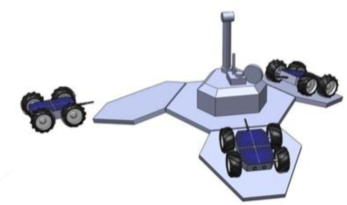


Examples of Extreme Terrain Vehicles

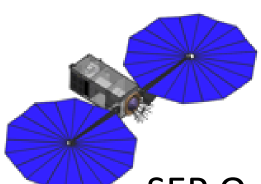
Selected ideas served as a catalyst for MPPG to charter sub-teams to explore lower cost approaches to sample return



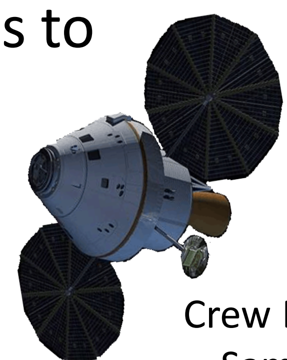
Microsats



Mini-Rovers



SEP Orbiter & Return to Beyond Earth Orbit



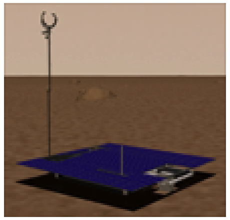
Crew Based Sample Return to Earth*

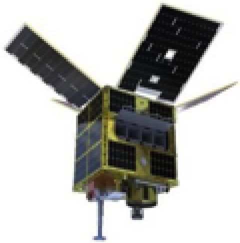
Mini-MAV

LPI Workshop – The Results in Context of MPPG

- Ideas for Smallsats/Cubesats to complement and augment orbital & surface measurements
  - Including opportunities for student experiments

- P-POD dispensers on Mars orbiters and/or cube accommodation slots on landers may be feasible within the core mission options explored by MPPG





<u>Example Applications:</u>

- Phobos Sampling
- ChipSat Re-entry Sensors
- Radio Occultation
- Weather Network
- Climate Lander
- Atmospheric Sounding
- Human Health Risks

COLLABORATION BETWEEN HUMAN EXPLORATION, SCIENCE, AND TECHNOLOGY

Human Exploration at Mars

- HEOMD is demonstrating capabilities and reducing risk for human Mars exploration
  - *Near Term (2012-2022): Core Capability Development, Mid-Phase Risk Reduction*
  - *Mid-Term (2022-2033): Core Capability Operations and Upgrade and Late Phase Risk Reduction*
  - *Long Term (2033+): Humans at Mars*

- Primary risks to mitigate for in-space segment, including on ISS
  - *Life support*
  - *Spacecraft reliability, supportability and maintainability*
  - *Human performance for long durations in deep space*
  - *Transportation system performance*

- Understanding the risks to the crew of landing on, operating on, and then ascending from Mars, require additional measurements, technology, and systems development

Capabilities Needed for Humans at Mars in 2030's

Epoch of first use:

2012-2024

- Orion MPCV
- SLS Initial Capabilities: 70 – 105 t
- Interim Cryogenic Stage
- 21st Century Ground Ops

2024-2033

- Large Propulsive Stage
- Deep Space Habitat (365 days)
- 300kW+ SEP Stage
- Orion+ Upgrades

2033+

Mars Orbit

- SLS Upgrade (130t)
- Deep Space Habitat (900 days)
- Advanced Propulsion (e.g., NEP, NTP)

Capability architecture to Mars System under study

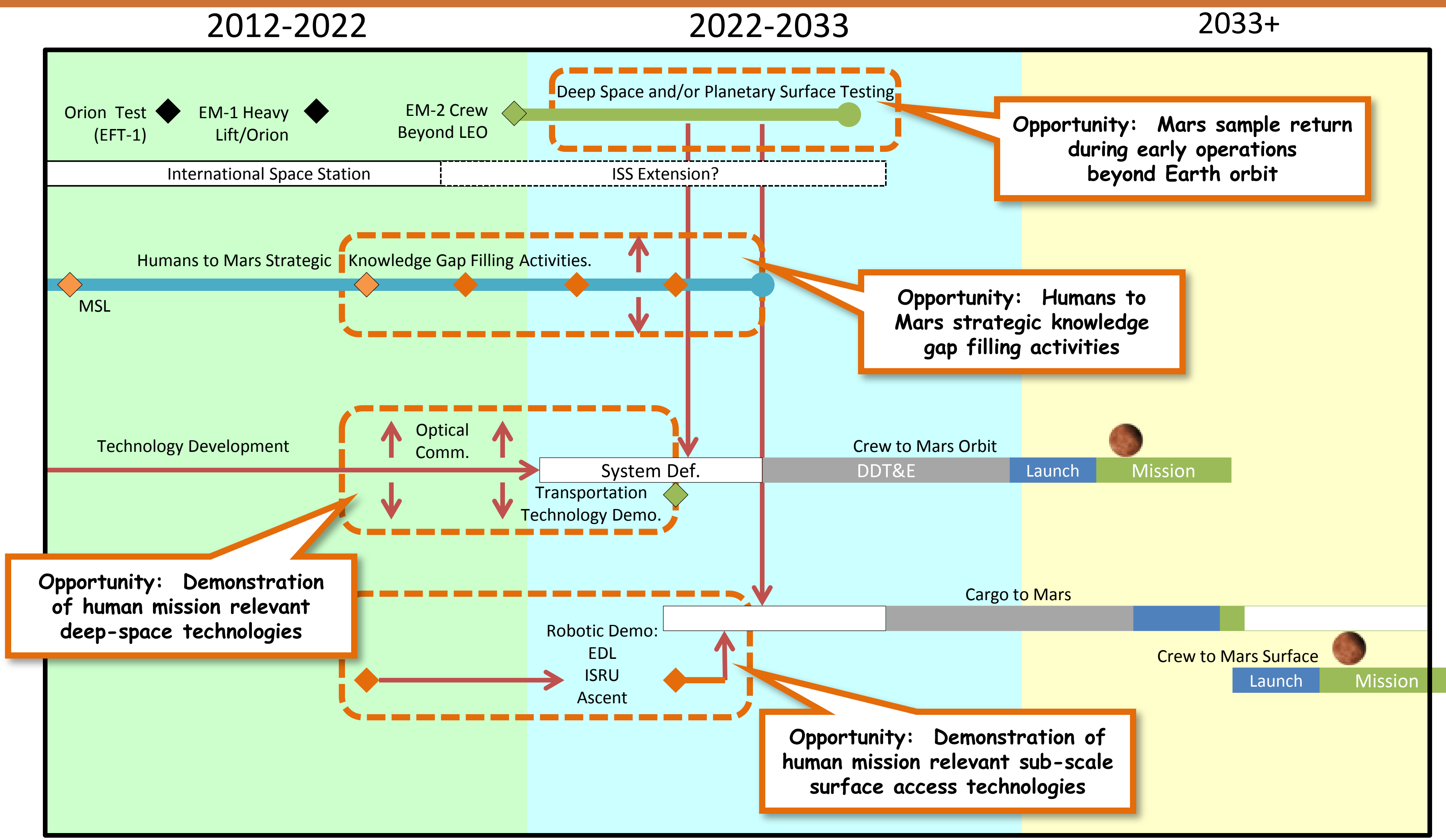
Mars Surface

- Lander
- Ascent Vehicle
- ISRU
- Surface Habitat
- Surface Suit
- Rover

Robotic demonstration of human mission relevant sub-scale surface access technologies can support EDL, ascent and ISRU

Building up system capabilities, gaining deep space operational experience and reducing risk as we move further out into the solar system

Human Exploration / Science / Technology Intersections



For MPPG Planning Purposes – Pre-Decisional

Defining Types of Collaboration

- **Clean-Interface Collaboration** ***(payloads, demo's, SKG fillers)***
  - HEOMD experiments piggyback on SMD missions, such as ODYSSEY, MRO, PHOENIX, MSL
  - No critical dependencies
  - All architectures/science pathways can support these

- **Interdependent Collaboration**
  - Joint activities associated with greater capabilities, such as high data rate communication, higher-mass EDL, surface power, ascent technologies, advanced sample handling and isolation, resource utilization
  - Dependencies that require cooperative management, shared resources, and agreement on approach to achieve the missions
  - Program linkages at each step, culminating in capabilities required for human access to Mars
  - <u>SOME EXAMPLES</u>:
    - Orbiters that image, discover resources, measure atmospheric state
    - Landers that provide ground-truth and identify samples (context)
    - Landers that demonstrate safety, EDL (e.g. MSL), resource utilization experiments

Opportunities for Collaboration between Human Exploration and Science

- In the process of preparing for the human exploration of Mars, several opportunities exist for collaboration between human exploration and science
  - Science-focused missions provide opportunities for measurements of the Martian system to fill Strategic Knowledge Gaps (SKG's)
  - HEO-developed launch capabilities may provide opportunities for science missions to reduce launch costs
  - Human capabilities and assets Beyond Earth Orbit (BEO) can play a role in retrieval and return of samples from the surface of Mars
  - Future robotic technology precursor missions provide additional opportunities for access to the martian system for scientific objectives

Science/Human Exploration/Technology

✓ Addressed in architecture and mission options presented by MPPG

Technology on Orbiting/Landed Assets

✓High Data Rate/Bandwidth Communications
✓Precision Navigation
✓Enhanced Surface Mobility
✓Targeted Observation/Instrumentation
✓Sample Acquisition, Handling and Caching
✓Autonomous Rendezvous and Docking
✓Advanced SEP Propulsion
✓Mars Ascent Vehicle
✓ISRU demo
✓Robotic Aerocapture
✓Robotic Scale EDL

Science/Precursor Measurement Payloads on Orbiting/Landed Assets

✓Environmental Measurements
- Radiation
- Atmospheric properties
- Climate

✓*Resources (Orbiters or Landed Tech Demos)*
✓*Dust & Regolith Properties/Safety*
✓Site identification/selection/certification

CONSTRUCTION ZONE: FORWARD WORK

Human Subscale Technology Demos with Opportunities for Science/Precursor Measurements

- 10% Subscale of human mission EDL
- Hypersonic Inflatables (HEO/HIAD)
- Mid-L/D Rigid Aeroshells
- Supersonic Retro-propulsion
- ISRU (Oxygen) Production
- ISRU-Enabled Mars Ascent Vehicle
- Aerocapture
- Advanced TPS including High-speed Earth Return

- Requires long term investment in technology
- Tips the scale to different architecture and scale of missions beyond typical robotic missions

HEO Measurement Options on Robotic Missions

MEPAG Precursor Science Analysis Group report* emphasizes measurements of Mars' atmospheric conditions and the surface radiation environment to reduce risk and also provide significant science value.

Robotic Orbiter(s)

- Orbital atmospheric information related to MOI/EDL.
- Radiation—simultaneous orbital and surface measurements valuable.
- High resolution imaging and mineral mapping of the surface support:
  - Forward PP assessments
  - Landing site identification, selection and certification
  - Resource identification

Robotic Lander/Rover(s)

The following measurements could be made from landed assets:

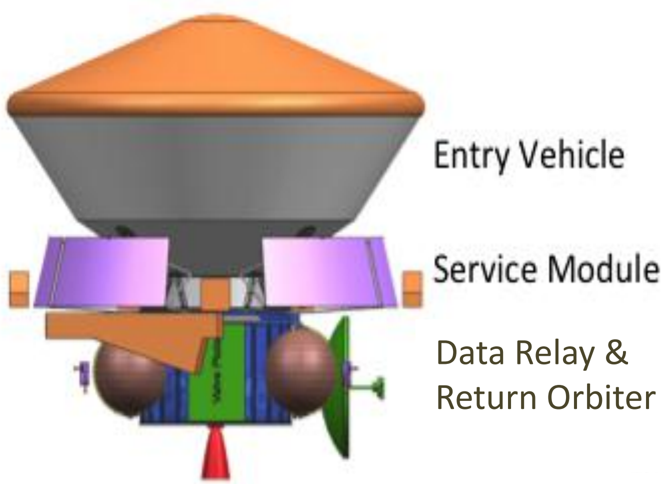
- EDL profiles of atmospheric state
- Dust properties, regolith composition, regolith structure
- Atmospheric electrical characteristics
- Atmospheric and climate measurements to obtain time dependent density profiles (simultaneous with orbital measurements).
- Radiation measurements (simultaneous with orbital measurements).

*(http://mepag.jpl.nasa.gov/reports/psag_files/P-SAG_final_report_06-30-12_main_v26.pdf)

Opportunity: Science Payloads on SLS

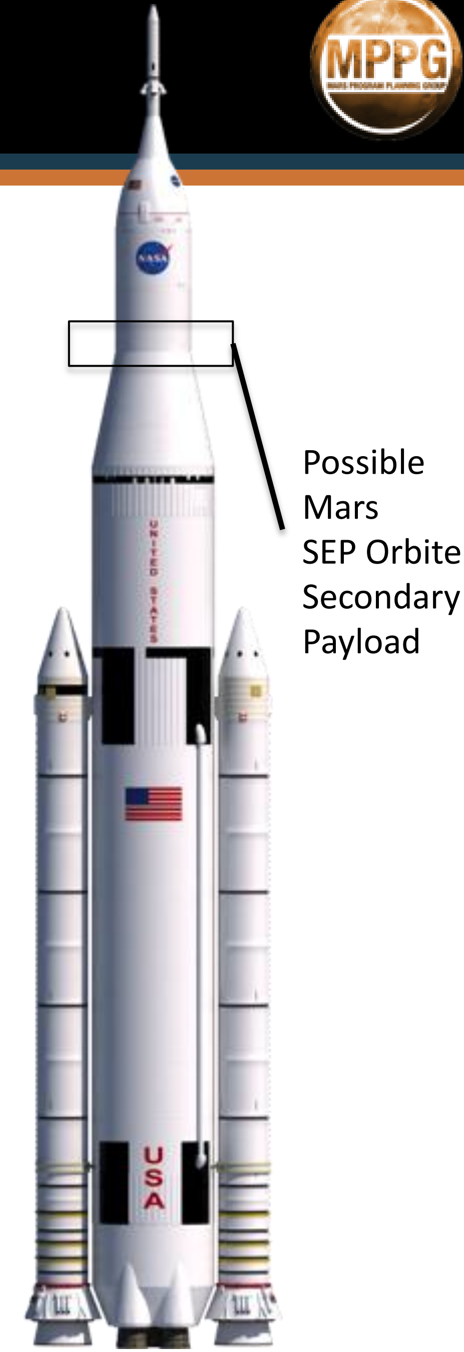
2024+ single-shot MSR on SLS

- Launch cadence and availability may provide a single-shot Mars Sample Return (MSR) opportunity; backup would be Delta IV Heavy or Falcon 9H



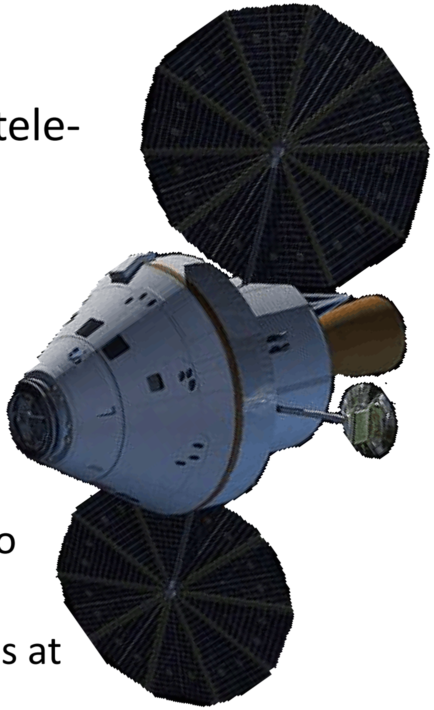
Integrated Stack

Integrated Stack
inside
5 meter faring



Opportunity: Mars Sample Recovery & Return During Early Crewed Operations Beyond Earth Orbit

- SEP-enabled robotic vehicle delivers samples to Beyond Earth Orbit (BEO) for a crew based retrieval
  - Beyond Earth Capability planned for after 2021



- Sample canister could be captured, inspected, encased and retrieved tele-robotically
  - Robot brings sample back and rendezvous with a crewed vehicle
  - Cleaned sample canister would be then enclosed in a stowage case, and stowed in Orion for Earth return.

- This approach deals with key planetary protection concerns
  - Crew inspection, cleaning, and encapsulation of sample enclosures prior to Earth return
  - Removes the need to robotically "break the chain" of contact with samples at Mars, thus reducing complexity and cost of robotic missions.

- Crew entry system eliminates need for robotic Earth entry system

- Provides an early opportunity for collaboration and demonstration of capability also applicable in Mars orbit

Intersections & Opportunities: Science, HEO, Technology Mission Options

	Near-Term Orbiters & Landers		Mid term Lander 1	Mid term Lander x
Early BEO Crewed Operations			MSR Rendezvous with Crew *	→ MSR Rendezvous with Crew
Technology Development and Demonstration: In-Space Segment	Orbiter Tech Demo Options: Optical Comm. Atomic Clock High Efficiency SEP	Rendezvous techniques, SEP proof of concept <50kW →		
		Feeds mission mode decision		
Measurements/SKGs	Orbiter Options: Science, Radiation, Atmospherics	Lander Options: MEDLI-2 Dust, Climate, Radiation		
Technology Development and Demonstration: Surface Access and Ascent Segment		Lander: In Situ O2 Production Demo (proof of concept) →	ISRU-based MSR MAV demo →	ISRU-based MSR MAV*
SLS Launch Opportunities		Potential secondary payload →	Potential secondary payload →	Dedicated: High value MSR*

* Would be moved up if budget allows

TECHNOLOGY

Technology Taxonomy and Development / Demonstration Approach

- *Mars technology needs span across science and HEO missions*
  - *Some are unique, but many are common or can be demonstrated on a common mission*
- *Mars technology demonstrations may be conducted at Earth or Mars*
  - *Demonstration environment and mission application can be scaled to meet specific demonstration objectives*

Increasing Fidelity, Cost

Mars-based

Technology Demo Mission

Examples:
- Sub-scale Human EDL (e.g. HIAD)
- Sub-scale ISRU MAV

Technology System/Subsystem (in-line)

Examples:
- MSL Guided Entry
- First Mars SIAD/HIAD use
- First MAV at Mars

Technology Payload on Science Mission

Examples:
- Optical Comm
- Atomic Clock
- ISRU proof-of-concept

Earth-based

ISS/LEO, Beyond Earth Orbit (BEO)

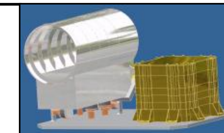
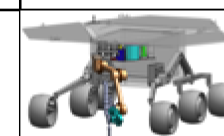
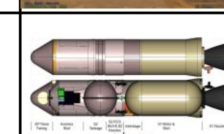
Examples:
- Closed loop high rel. life support
- NEP, NTP Propulsion
- Low boil-off Cryo propulsion

Ground or Sub-orbital

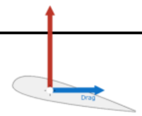
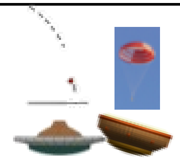
Examples:
- STP LDSD/SIAD, HIAD
- Storable MAV development
- Surface Fission Power

SMD/STP Technology Efforts with HEOMD Benefit

*In addition to EDL and ISRU, the following **crosscutting** technologies are being developed today by STP (†) and SMD (*) to support future robotic and human exploration:*

Optical Communications†	High bandwidth, high data rate communication from Mars. Enable order or magnitude or more increase in data rate, and video/voice streaming	Infusion Target: Early Opportunity Orbiter	
Deep Space Atomic Clock†	Precision Navigation for orbital assets, Entry, Descent and Precision landing. Reduces scheduling burden of ground network, enabling significant cost efficiencies	Infusion Target: Early Opportunity Orbiter	
Solar Electric Propulsion†*	Large solar arrays, higher power, high thrust Hall thrusters. Enables flexibility in implementation of the architectures	Infusion Target: Early Opportunity Orbiter	
Sample Acquisition, Handling and Caching*	Enable access and sampling at the surface, analysis. Securing for transfer to another vehicle, and return	Infusion Target: Early Opportunity Lander	
Autonomous Rendezvous and Docking†	Sensors and software to autonomously detect, rendezvous and capture the orbiting sample canister in orbit.	Infusion Target: MSR Orbiter	
Mars Ascent Vehicle	Mars Ascent Vehicle to deliver surface samples into low Mars orbit (including ascent flight dynamics). Conventional non-cryogenic liquid or solid propellants	Infusion Target: MSR Lander	
Large Deployable Supersonic Decelerators†	Next generation deceleration technologies to enable evolution to 1.2-1.5 t landed mass robotic missions from current SOTA < 1 t. Enable greater planet access	Infusion Target: Early-Mid Term Opportunity Lander	

Key Technologies for Entry, Descent & Landing

Approach Phase		Near-Term Robotic (1-2t)	Sub-scale EDL Precursor (~5 t +)	Human Full-Scale (20-40t)	
Approach Navigation	Precision Star Tracker, Late Update, Optical Nav, Precision IMU	●	●	●	
Entry Phase					
Atmospheric Guidance	Lift Modulation, Drag Modulation	●	●	●	
Hypersonic Decelerators	Deployables: HIAD, ADEPT	○	○ OR	● OR	
	Rigid: Slender body Aeroshell		○	●	
Descent Phase					
Supersonic Decelerators	Smart Descent/Deploy Logic	●	○	○	
	30m Supersonic Parachute	●			
	SIAD	●	○	○	
Supersonic Retro-propulsion	High-thrust liquid		○	●	
Landing Phase					
Surface sensing and navigation	Terrain Relative Navigation, ALHAT, Hazard Detection and Avoidance	●	●	●	
Subsonic Propulsion	Storable (Monoprop/biprop), Cryo (biprop)	●	●	●	
Energy Absorption	Airbags, Crushables	●			
High-g Systems	Rough Lander	○			

Potentially Applicable ○

Fully Applicable ●

Investment Priorities

Key Technologies for ISRU and Mars Ascent

- *Demonstration of ISRU generation of propellants (O_2 and CH_4), followed by an ISRU-enabled MAV provides significant risk reduction for humans to the surface of Mars*
- *Mars Ascent Vehicle (MAV) is unique in needs for long-term propellant management (storage and/or production) in a challenging thermal environment*

ISRU		Near-Term Robotic	Sub-scale Precursor	Human Full-Scale	
Processing	Atmospheric Processing for Liquid Oxygen		●	●	 
	Fuel processing of Surface Available Hydrogen (Ice/Hydrated Mineral Processing)		○	○	
	Other materials – Construction, Radiation Protection		○	○	
Propulsion	LOX/Methane		●	●	
Mars Ascent Vehicle (MAV)		Near-Term Robotic Storable (.2-.3 t)	Sub-scale Precursor ISRU MAV (TBD)	Human Full-scale ISRU MAV (20+ t)	
Propellant Type	Solid vs. Liquid	●	Liquid	Liquid	
Propellant Production	Ox only vs. Ox + Fuel		●	●	
Thermal Control	Isolation from Mars Environment	●	●	●	
Payload Loading	OS Loading, Break-the-Chain	●			

Potentially Applicable ○

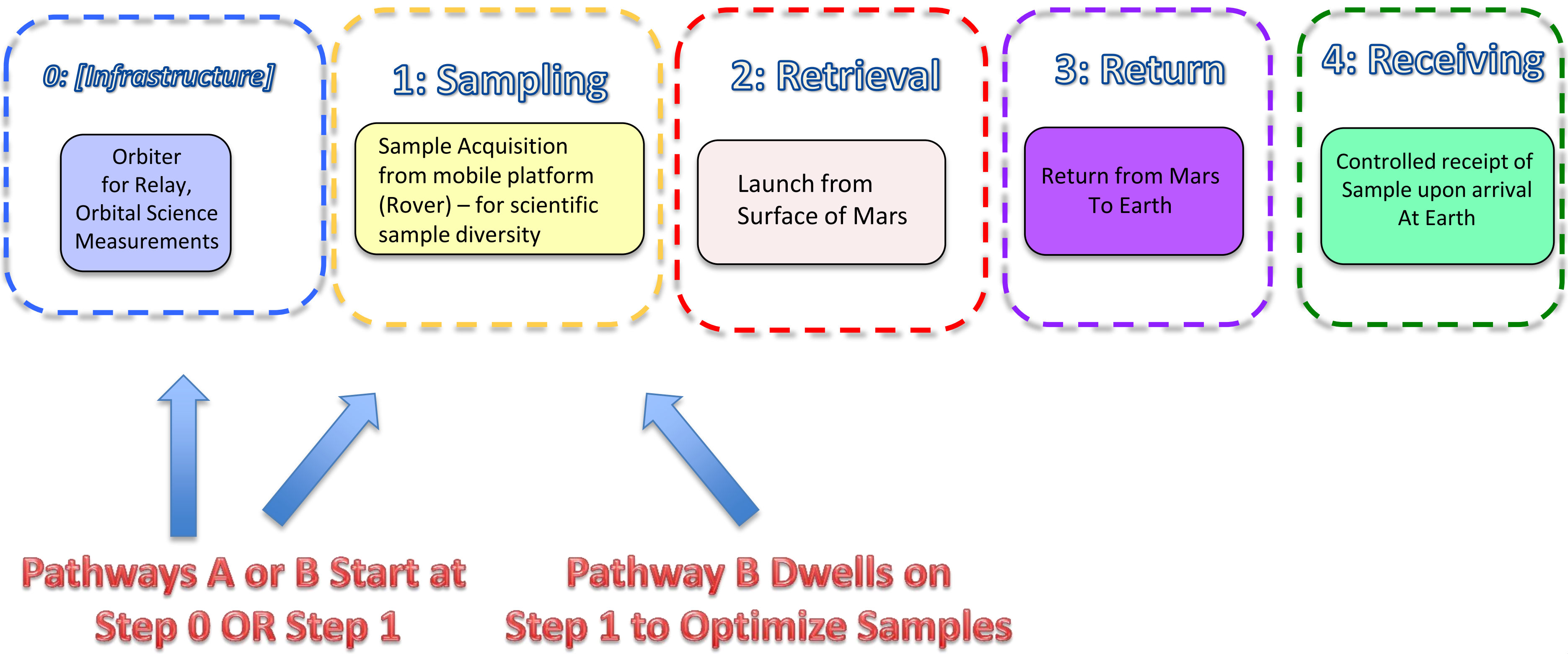
Fully Applicable ●

Investment Priorities

POSSIBLE PROGRAM ARCHITECTURES:
IMPLEMENTATIONS OF HIGHEST PRIORITY SCIENCE PATHWAYS

Key Functions in Sample Return

- Five functional elements are required to return samples from Mars
- These functions can be accomplished in multiple ways and by one or more missions

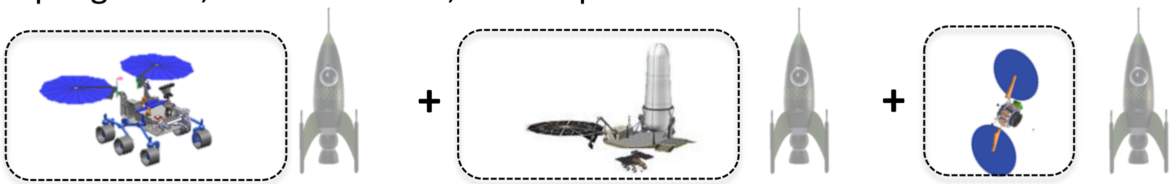


Sample Return Launch Options

- Mars Sample Return (MSR) can be implemented by breaking the mission into different “Launch” and “Landing” Packages
- MPPG looked at accomplishing MSR in 1, 2 or 3 launches with various cost, cost profile and risk implications

<u>Three launches</u>

- This is the architecture proposed to the Decadal Survey
  - 1- Sampling Rover, 2- MAV + Fetch, 3- Sample Return Orbiter

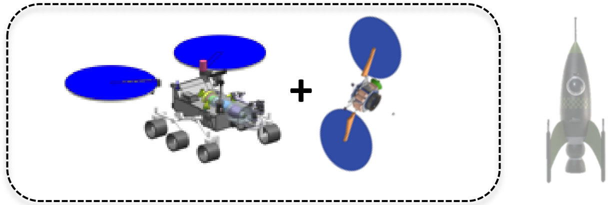


<u>Two Launches</u>

- Sampling Rover paired with a second launch (MAV/Fetch + Small SEP Return Orbiter) to accomplish a “Two Launch MSR”

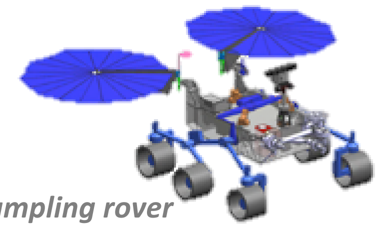
<u>One Launch</u>

- Sampling rover carrying a MAV, co-manifested with a small SEP orbiter to bring the sample back to Earth/Moon system



Pathway A1: Multi-mission MSR

Optional



Sampling rover

\+

Static MAV & fetch rover

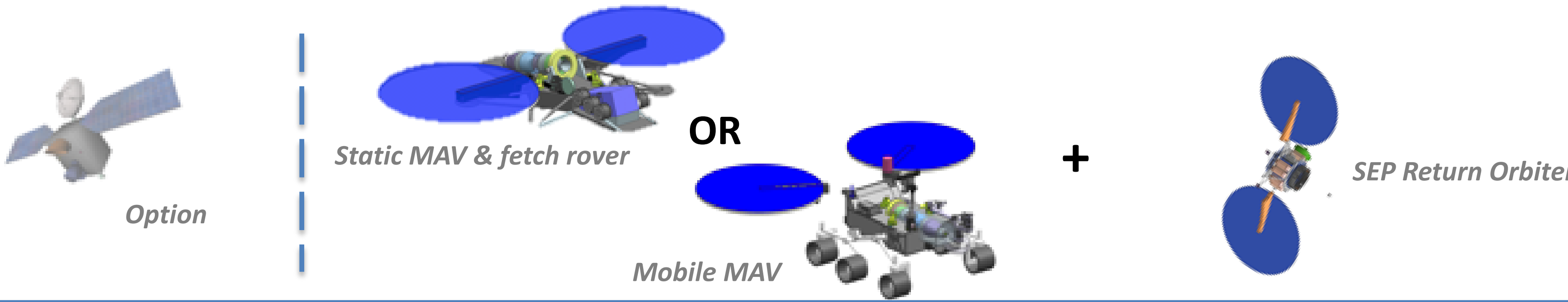
\+

SEP Return Orbiter

- Architecture for Pathway A1 is multi-mission:
  - New sampling rover concepts have reduced costs by ~50% from prior MAX-C/ExoMars missions evaluated as part of the NRC Decadal Survey (independently costed)

- <u>Architecture Features:</u>
  - Decouples sample acquisition and MAV missions
  - Allows large time allocation for sample acquisition without concern for MAV survival on Mars surface
  - Spreads technical challenges across multiple missions
  - Provides landed mass margins within family with existing MSL CEDL capability
  - Spreads budget needs and reduces peak year program budget demand
  - Missions have opportunities for additional orbital/in situ science
  - Sample return orbiter can be integrated into single launch (e.g. SLS, Falcon heavy) with MAV lander or combined/co-manifest with other missions

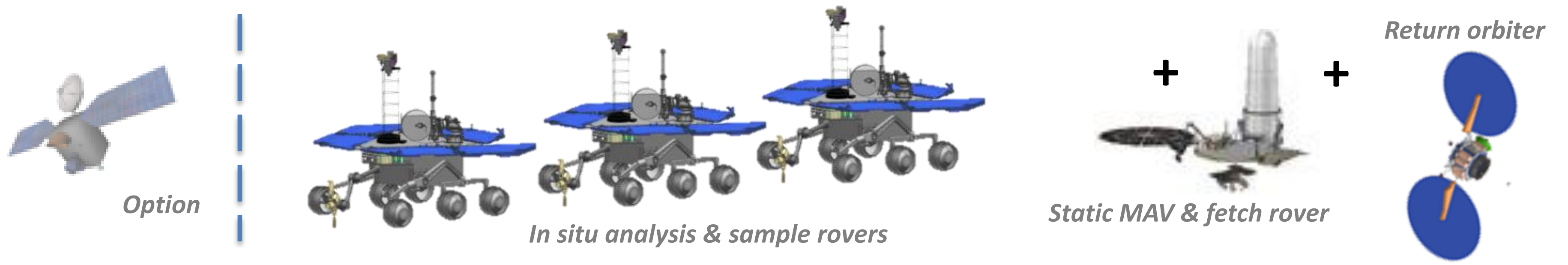
Pathway A2: Integrated Sampling/MAV MSR



- Architecture for Pathway A2 pursues a cost-driven MSR approach with fewer discrete spacecraft-vehicles/launches:
  - Consolidation of functions are made to significantly reduce the life-cycle costs
  - Extensive option space enumerated, and 7 representative options were detailed

- <u>Architecture features:</u>
  - Landed mission integrates sample acquisition via rover and either fixed platform MAV or mobile MAV into one lander (compared to Pathway A1) and saves the cost of a lander and a launch vehicle
  - Sample return orbiter can be integrated into single launch (e.g., SLS, Falcon heavy) with lander or combined/co-manifest with other missions
  - Mobile MAV eliminates surface mission coordination complexities
  - Lowest overall costs due to elimination of at least one complete mission, but higher peak year budget demand

Pathway B: Multi-Site Investigation Before MSR



- Architecture for **Pathway B** employs multiple rovers delivered to independent sites that are investigated to provide detailed understanding of their habitability and bio-signature potential and the optimal sample suite is returned to Earth

- <u>Architecture features:</u>
  - Provides potential to blend in situ science and sample collection at a pace to accommodate available budget
    - Once the selection of the returned sample suite is made, this Pathway utilizes the same Earth return architecture as Pathway A
  - Production line build of the rovers and cadence of launches offers the opportunity to significantly reduce the cost (in comparison to multiple independent missions)

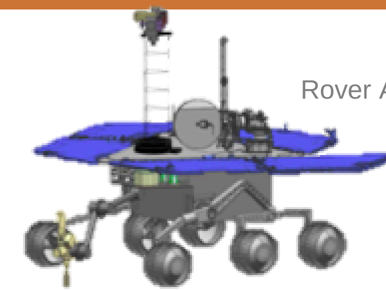
Common Aspect of All Pathways

- Maintained heritage from MSL/MER Cruise/EDL and rovers
- Take advantage of guided entry for MSL-class landing accuracy
- All MAV landers utilize as-flown MSL *SkyCrane* capabilities
- Incorporated innovative ideas from past studies and concepts presented at LPI
- Reduced mass of MAV/OS (guided or unguided) can be launched to either deep space or Mars orbit, providing flexibility for return orbiter timing/availability
- Using SEP-based orbiters for sample rendezvous and return
  - Return of sample canisters to crew in BEO (Earth-Moon neighborhood) to be captured by astronauts and returned to Earth [eliminating Earth entry vehicle]
  - Potential co-manifest with other vehicles
- Have options to use lower cost LVs

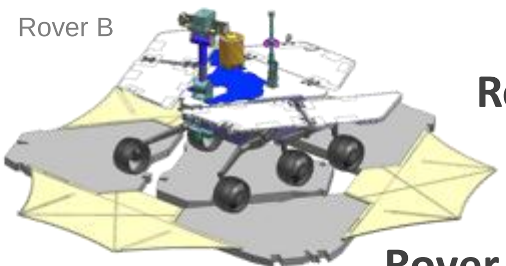
SURFACE AND ORBITAL MISSION CONCEPTS

Sampling Rover Concepts Studied

Four rover options studied

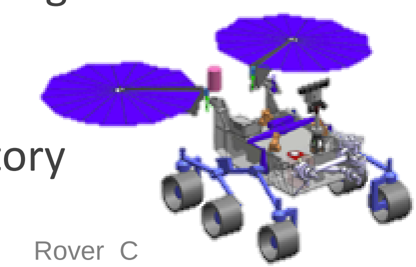


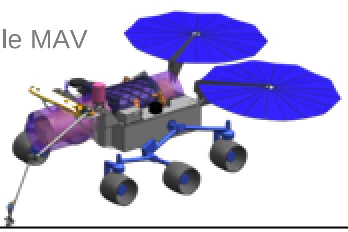
Rover A: MER "clone" allowing for sampling and replacing obsolete avionics. Might not fit in the MER volume envelope



Rover B: Similar to Rover A allowing for some volume growth

Rover C : based on MSL delivery and chassis, with inventory reuse and some de-scopes (e.g., solar vs. RTG)





Rover D: derived from Rover C with MAV integrated into vehicle and carried to sampling sites

- Costs reduced from Decadal Survey concept by maximizing heritage and reducing scope and complexity:
  - Developed payload concept compatible with either a MSL or MER rover class
    - All rovers designed for latitudes -15 to +25
  - Strong heritage from MSL and MER, especially C/EDL
    - All rovers delivered with MSL-class accuracy using guided entry (upgrade to MER-based concepts)
    - Landing altitude capability of up to -0.5 km w.r.t. MOLA reference

Rover Concepts Comparison (1)

Rover A

- MER-based system w/ guided entry addition
- Build on successful MER design heritage.

Advantages

- Heritage MER mechanical structures and EDL systems
- High EDL heritage
- Feed forward applicability to small surface missions
- Low recurring costs
- Low launch vehicle costs (Falcon 9 v1.1)

Challenges

- Very limited payload/volume margin

Costs Estimates

Internal	$1.1B
Aerospace ICE	$1.0B
Aerospace CATE	$1.0B
LV (F9)	$0.16B ('18) / $0.19B ('20)
Phase A-D	**~$1.1 - 1.3B**

Rover B

- Scaled MER-based system w/ guided entry addition
- Build on successful MER architectural heritage.

Advantages

- Robust to inheritance assumptions (new systems)
- Feed forward applicability to small/mid surface missions
- Low recurring costs
- Low launch vehicle costs (Falcon 9 v1.1)

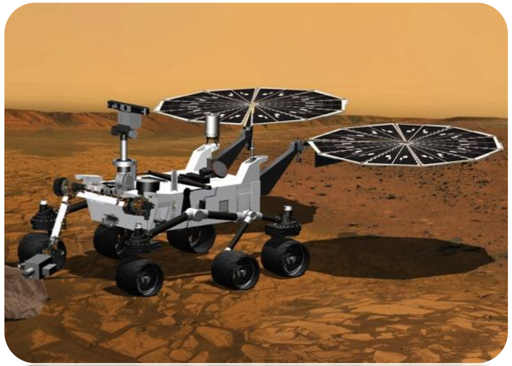
Challenges

- Requires new airbag & touchdown system development

Costs Estimates

Internal	$1.2B
Aerospace ICE	$1.1B
Aerospace CATE	$1.1B
LV (F9)	$0.16B ('18) / $0.19B ('20)
Phase A-D	**~$1.3 - 1.4B**

Rover Concepts Comparison (2)



Rover C

- Solar MSL-based system
- Build on successful MSL design heritage.

Advantages

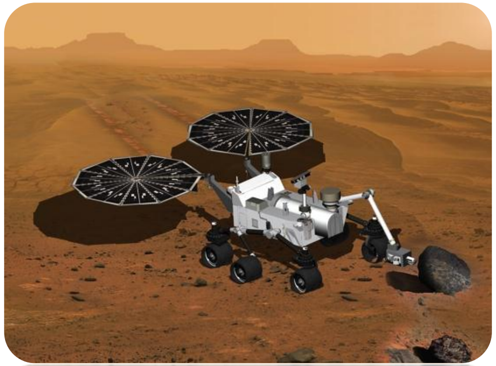
- Robust to payload growth
- Substantial HEO/STP payload opportunity
- Best mobility range/life/mission return
- Substantial redundancy
- High EDL heritage
- Feed forward applicability to large MSR / MAV missions

Challenges

- High launch vehicle costs (Atlas)

Cost Estimates

- Internal $1.0B
- Aerospace ICE $1.1B
- Aerospace CATE $1.3B
- LV (A5) $0.32B ('18) / $0.40B ('20)
- **Phase A-D ~$1.3 - 1.7B**



Rover D

- MSL-based system with integrated MAV
- Build on successful MSL heritage.

Advantages

- Provides capable surface science platform
- Supports agency MAV demonstration / return capability
- Best mobility range/life/mission return
- Substantial redundancy
- High EDL heritage
- Can be coupled w/ return orbiter for lowest MSR cost

Challenges

- Rover mechanical mods; MAV development; and LV costs

Cost Estimates (STILL UNDER DEVELOPMENT)

- Internal ~$1.4B estimate only
- Aerospace ICE N/A
- Aerospace CATE N/A
- LV (A5) $0.32B ('18) / $0.40B ('20)
- **Phase A-D TBD**

Orbiter Concepts Studied

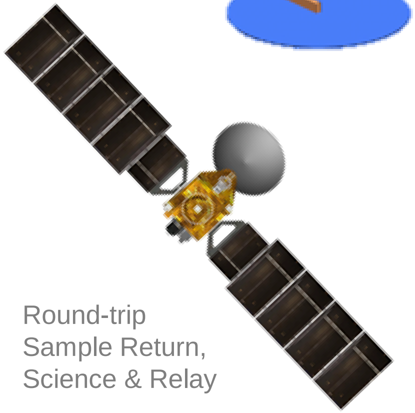
- Orbiters play multiple roles in architectural framework
  - Telecomm. Relay Infrastructure:
  - Programmatic infrastructure to provide landing site identification/selection/certification
  - Ongoing or new measurements from orbit—e.g., hi-res imaging/mineral mapping, resource identification, HEO gap-filling measurements for Strategic Knowledge Gaps (SKG's)
  - Sample Return from Mars orbit to Earth

- Several orbiter concepts developed that combine one or more of these functions:
  - **Relay-only** infrastructure orbiter – Might use Solar Electric Propulsion enabling co-manifest with other mission to partially eliminate launch cost
  - **"Traditional" Science + Relay** Orbiters (a la MRO, ODY) using combinations of chemical and aeroassist propulsion
  - **Sample return orbiters –** Meets up with samples either at: a) Low Mars Orbit (chemical or Solar Electric Propulsion); or b) deep space rendezvous (SEP only). Might also co-manifest with landers
  - **Round-trip Science + Sample Return** Orbiters can launch early, perform science mission and return to Earth after landed missions conclude


Relay Only


Traditional Science & Relay


SEP Sample Return


Round-trip Sample Return, Science & Relay

Orbiter Concepts Comparison

Single Function Orbiter

- New system
- Can be used for UHF or Sample return
- Single String Design (redundant option to fly 2)

Advantages

- Simple design
- Additional units lower cost
- Can deliver more frequently
- Very low launch cost as secondary payloads

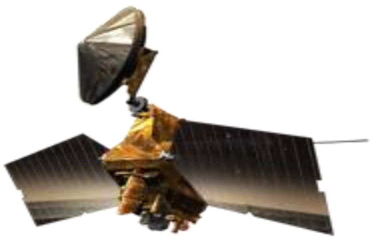
Challenges

- Very limited payload
- Limited Lifetime

Costs Estimates

- Internal $0.2 B

(no payload, launch as secondary)



Science + Relay Orbiter

- MRO/MAVEN based
- Science and tech demo payloads

Advantages

- High bus heritage
- Infrastructure/science instruments have robust heritage
- High data volume
- Large payload capacity

Challenges

- Compatible orbit selection for science and relay

Costs Estimates

- Internal $0.5 B
- Aerospace ICE/CATE $0.6 B
- LV (F9) $0.13 B

SEP Sample Return Orbiter

- New system
- Commercial Components

Advantages

- Co-manifest with Lander
- Augments LV capacity
- Commercial SEP components

Challenges

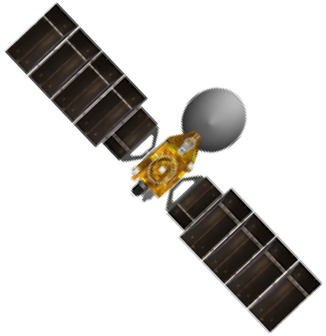
- No EDL relay support

(arrives later)

Costs Estimates

- Internal $0.5 B

(Lander carries launch cost)



Science + Sample Return Orbiter

- MRO/MAVEN Based
- Can support science, relay, tech demo, and sample return

Advantages

- Science and Relay while waiting
- High bus heritage
- Commercial SEP components
- High mass and data volume
- Very large payload capacity

Challenges

- Break-off orbital science to return samples to Earth

Costs Estimates

- Internal $0.7 B
- LV (F9) $0.13 B

COST PICTURE AND THE EARLY OPPORTUNITIES

Cost Analysis Process

- Cost estimates developed for candidate missions, then used to populate different program queues, and ultimately assessed for compatibility with President's FY13 Budget Submittal
  - Scenarios to explore what is possible with augmented funding were also considered

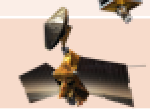
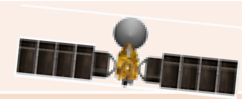
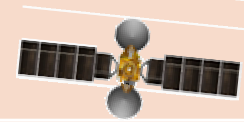
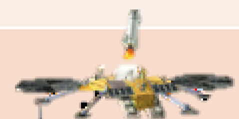
- Depending on the maturity and anticipated timeliness of launch for each concept, estimates of varying depth/fidelity were developed:

G – **Gold Standard:** Independent Cost Estimate (ICE) + Cost and Technical Evaluation (CATE) performed by Aerospace Corporation – equivalent to Decadal Survey Process. Core estimates from study team based on AS BUILT missions (MSL, MER, MRO)

S – **Silver Standard:** Parametric Model, Team X Study, Cost by analogy to previously developed systems

B – **Bronze Standard:** "Guesstimate" – Expert opinion, interpolated between or extrapolated from other data points of Class A or Class B estimates

2018-2024 Example Missions

ID	Function	FY15 $(B)*	Visual	Estimate Standard
Orbiters				
A	Single Function SEP Orbiter, e.g. UHF, Earth Return (Secondary Launch Option)	**TBD**: ~0.1– 0.2		S
B	Comm.+ HR Camera + Mineral Mapper	0.6 – 0.7		G
C	Orbiter B + Optical Comm.	0.6 – 0.8		G/S
D	Orbiter C + Extended Science (e.g., SAR, SOFTS)	0.7 – 0.9		G/S
Landers				
A	MAV on Stationary Lander + Fetch Rover	**TBD**: ~1.8+		S
B	Rover A/B	1.1 – 1.4		G
C	Rover C	1.4 – 1.6		G
D	Rover C + MAV (Mobile MAV)	**TBD**: ~1.8+		S
E	Athlete + MAV Demo	TBD		B
	**Costs Phase A-D, including launch (except Orbiter A)*			

Orbiter or Rover First ?

Arguments for Orbiter First

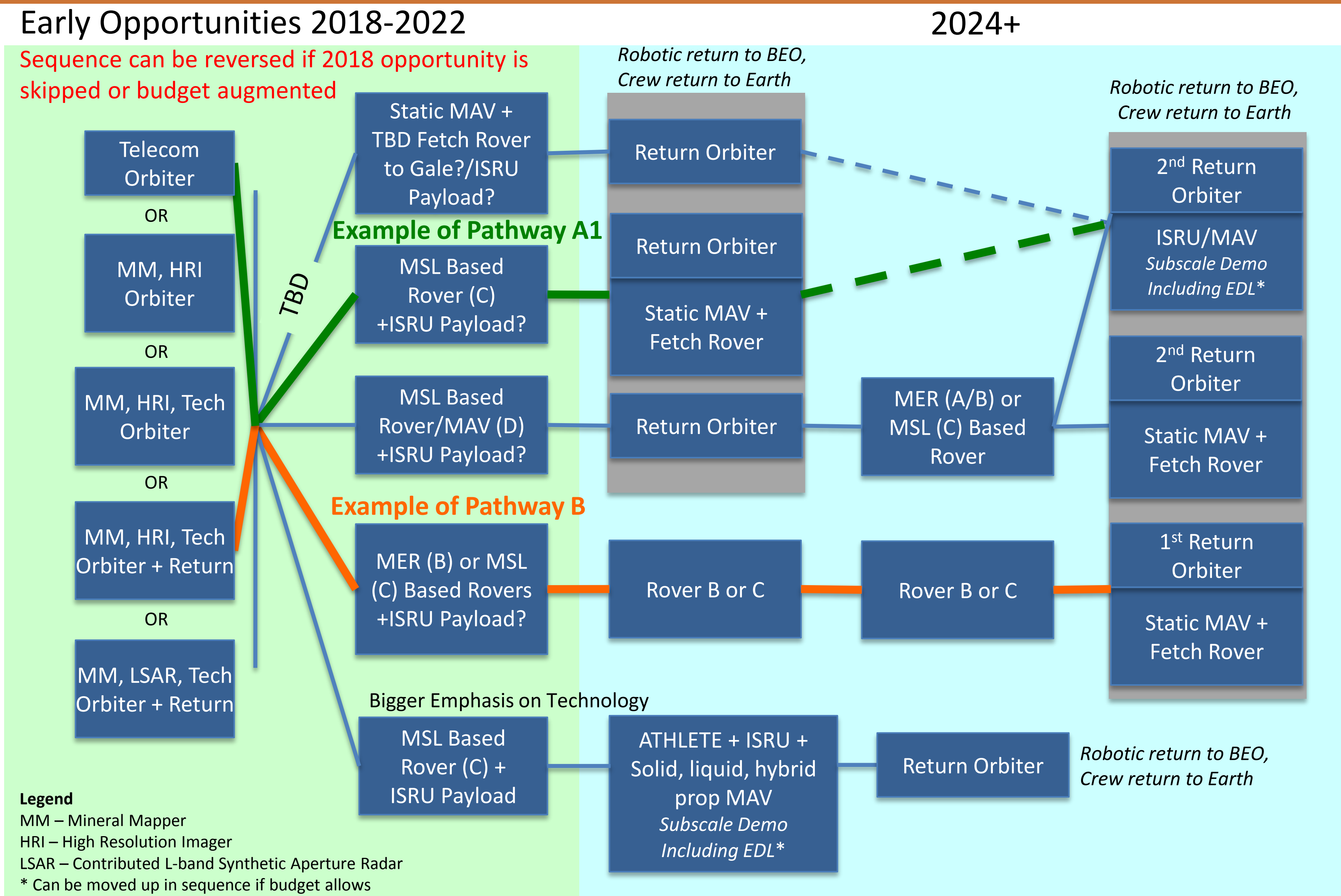
- Orbiter in ’18 provides infrastructure to all landed missions in ‘20-’26
  - *Existing orbiter network can likely support ’18 landed mission, but risk increases after ’20*
- Provides new science for enhanced surface site identification, selection, certification to support all Pathways and future human landing sites
- FY13 President’s budget does not support a rover in 2018 (2020 earliest)

Arguments for Rover First

- ‘18 provides one of the most energetically favorable launch opportunities
- Rover in ’18 or ‘20 best for preservation of key competencies such as End-to-End EDL and Surface Science Operations and Mobility
- Leverages MSL surface experience to identify/select/analyze/secure high science value samples at a priority site for further study and potentially return

Example Options for Strategic Collaboration

Science / Human Exploration / Technology



Input for Follow-on Benefits Assessment

ORBITERS (~$800M Budget Target)

- **Telecomm:** Telecomm infrastructure (required by 2022/24). Option to launch on SLS
- **Add Science:** Mineralogy, High Res. Imaging, Other contributed?
- **Add Technology:** Optical comm or Atomic clock
- **Add SEP Sample Ret Vehicle:** Initiate Sample Return

SURFACE MISSIONS (~$1500M Budget Target)

- **MER-class rover:** Supports MSR; Sustains EDL competencies
- **Multiple MER-class rovers:** Supports MSR; Sustains EDL competencies; Improves surface science; Stretches MSR
- **MSL-class rover:** Supports MSR; Sustains EDL competencies; Addl technology & surface science
- **MSL-class rover with MAV:** Initiates MSR; Sustains EDL competencies; Addl technology

Legend

Decadal Science; Knowledge Gap for HEO; Technology Infusion; HEO/SMD Interconnect; Cost/Tech Risk; Ind/Intl Collaboration; Other Considerations

Correlation Against Figures of Merit: High Risk; Mod Risk; Low Risk

OTHER PROGRAMMATIC CONSIDERATIONS

International Collaboration

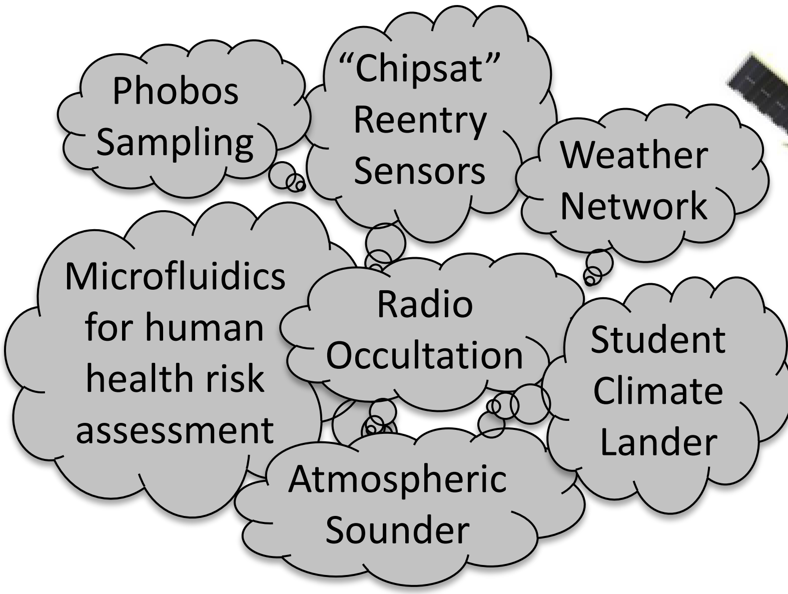
- **MPPG reached out to the international community, but only peripherally**
  - They attended/presented at LPI, and participated in follow up conversations to identify specific areas of collaboration (e.g. CSA interests in SAR and robotic arms)
  - Long standing conversations among HEOMD international partners continue through the International Space Exploration Coordination Group (ISECG)

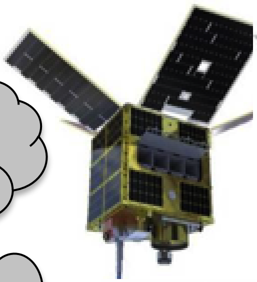
- **Exploration of Mars continues to be of interest to NASA's international partners, and is considered a necessary component to enable human missions to Mars**
  - Existing partners are expected to play critical roles in human exploration
  - Possible scenarios leading from ISS and LEO to Mars are being discussed to build a common vision, and leverage current investments in preparatory activities

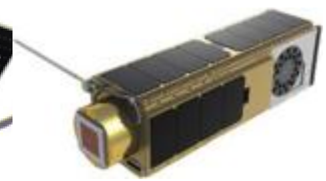
Smallsat / Cubesat / Student Payloads at Mars

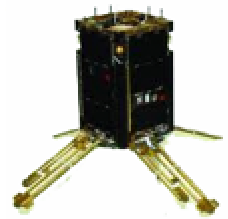
Small/Cube/Nano-Satellites, offer increasingly sophisticated measurement capabilities in small, low-mass (1 – 10 kg), low-power, low-cost ($1 – 10M) packages that are adaptable for Mars.

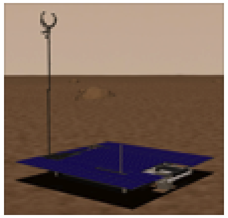
P-POD dispensers on Mars orbiters and/or cube accommodation slots on landers may be feasible within the mission options explored by MPPG











A Mars Program element can provide an opportunity for SMD/HEO/STP/OCT/OCS collaboration in further developing the technologies, compete for opportunities for multiple mission designs, and down-select for implementation

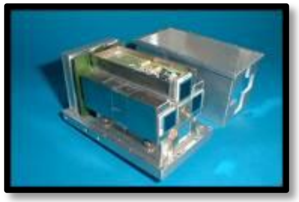
Research & Analysis Program, Instrument Technologies

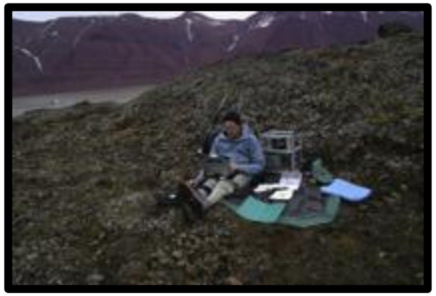
Mars science Research and Analysis programs

- Maintain healthy Science research activities to capitalize on data sets collected by on-going Mars missions
- Address fundamental understanding of Mars system science and signs of ancient life via bio-signatures
- Trade/maintain science pipelines

Mars instrument technology developments

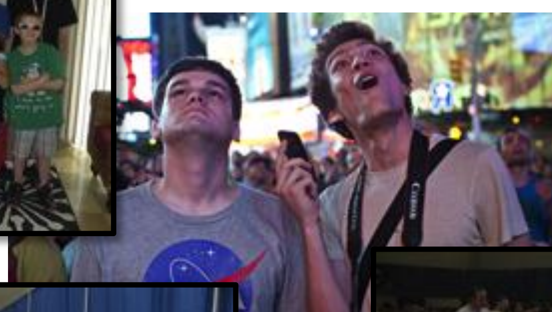
- Create/maintain instrument system technology development program to address future mission needs
- Pursue next generation/breakthrough remote sensing/in situ instrumentation/experiment concepts
- Reduce risks to future instrument development for Mars missions





Education & Public Outreach

- Mars activities provide world wide attention with potential to strongly motivate next generation talent in science, technology, engineering and mathematics
- Mars E/PO program has adopted a thematic approach (i.e. not mission by mission but program-wide) and has been excellent in its focus and reach
- Provide 1% of program funding for E/PO



MPPG SUMMARY

MPPG Summary of Findings and Observations

1. MPPG options address the primary objectives of the NRC Decadal Survey, with human exploration capabilities playing an increasing role over time, in the scientific exploration of Mars
2. Sample return architectures provide a promising intersection of objectives for long term SMD/HEOMD/STP collaboration, particularly in EDL and ISRU/Mars ascent technologies
3. MPPG offers several options to implement an integrated strategy for Mars exploration, providing flexibility and resiliency while recognizing the programmatic and fiscal challenges
   a. Provides a compelling science program, with sample return as a centerpiece in the overarching theme of Search for Signs of Past Life; endorses competition for other Mars science beyond the central theme
   b. Leverages robotic missions to fill Strategic Knowledge Gaps (SKGs) for human exploration and strengthen scientific collaboration
   c. Technologies and capabilities are identified that are of mutual benefit and enable humans at Mars orbit in the 2030's, with opportunities for increased collaboration in the future
   d. Options represent ~50% cost reduction compared to NRC Decadal concepts, and are responsive to Decadal objectives; implementation options include: 1) spreading risk and cost across several missions, 2) MSR in a single mission, and 3) improving probability of returning samples that preserve evidence of past life.
4. A variety of "building block" rovers and orbiters are suggested and costed, to facilitate planning of the new program architecture by NASA
   a. The building blocks provide options to specifically target the early mission opportunities
5. Return of samples to Beyond Earth Orbit (BEO) to be recovered by astronauts offers an early intersection of robotic and human flight programs, as capability is developed for human surface exploration of Mars

Gale Crater: Current *Curiosity* Position

Acronyms

A5 = Atlas V
ADEPT = Adaptable, Deployable Entry and Placement Technology
ALHAT = Autonomous Landing and Hazard Avoidance Technology
AO = Announcement of Opportunity
BEO = Beyond Earth Orbit
CAPS = NRC Committee on Astrobiology and Planetary Science
CATE = Cost and Technical Evaluation
C/EDL = Cruise, Entry, Descent, and Landing
CSA = Canadian Space Agency
DCSS = Delta Cryogenic Second Stage
DDT&E = Design, Development, Test & Evaluation
DSAC = Deep Space Atomic Clock
EDL = Entry, Descent, and Landing
EEV = Earth Entry Vehicle
EFT-N = SLS Exploration Flight Test #N (-1, -2, etc.)
EM-N = SLS Exploration Mission #N (-1, -2, etc.)
E/PO = Education & Public Outreach
FoM(s) = Figure(s) of Merit
F9 = Falcon 9
GFA = Gap Filling Activity
GSFC = Goddard Space Flight Center
HEOMD/HEO = Human Exploration and Operations Mission Directorate
HIAD = Hypersonic Inflatable Aeroassist Device
HQ = Headquarters
HRI = High resolution imager
HRP = Human Research Program
ICE = Independent Cost Estimate
IFM = In-Flight Maintenance
IMEWG = International Mars Exploration Working Group
InSight = Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport
ISECG = International Space Exploration Coordination Group
ISRU = In Situ Resource Utilization
ISS = International Space Station
JPL = Jet Propulsion Laboratory
JSC = Johnson Space Center
KSC = Kennedy Space Center
LDSD = Low Density Supersonic Decelerator Project
LEO = Low Earth Orbit
LMK = SLS Launch Mission Kit
LOX =Liquid Oxygen
LPI = Lunar and Planetary Institute
LV = Launch Vehicle
MAVEN = Mars Atmosphere and Volatiles Evolution
MAV = Mars Ascent Vehicle
MAX-C = Mars Astrobiology Explorer/Cacher
MEDLI = Mars EDL Instrumentation
MEP = Mars Exploration Program
MER = Mars Exploration Rovers
MEPAG = Mars Exploration Program Analysis Group
MM = Mineral mapper
MOI = Mars Orbit Insertion maneuver
MPCV = Multi-Purpose Crew Vehicle
MPPG = Mars Program Planning Group
MRO = Mars Reconnaissance Orbiter
MSA = MPCV Spacecraft Adapter
MSL = Mars Science Lander/Curiosity
MSR = Mars Sample Return
NAI = NASA Astrobiology Institute
NEP = Nuclear Electric Propulsion
NRC = National Research Council
NTP = Nuclear Thermal Propulsion
ODY = 2001 Mars Odyssey
OCS = Office of Chief Scientist
OCT = Office of Chief Technologist
OMB = Office of Management and Budget
OMS = Orbital Maneuvering System
OS = Orbiting Sample Container
P-POD = Poly-Picosat Orbital Deployer
P-SAG = MEPAG Precursor Science Analysis Group
POTUS = President of the United States
PP = Planetary Protection
RT = Round-trip
RTG = Radioisotope Thermoelectric Generator
SAR = Synthetic Aperture Radar
SDT = Science Definition Team
SEP = Solar Electric Propulsion
SIAD = Supersonic Inflatable Aeroassist Device
SKG = Strategic Knowledge Gap (for human exploration)
SMD = Science Mission Directorate
SLS = Space Launch System
STP = Space Technology Program
SRV = Sample Return Vehicle
TBD = To Be Determined
TLI = Trans-lunar Injection
UHF = Ultra-High Frequency